CLASSIFYING INFRASTRUCTURE IN AN URBAN BATTLESPACE USING THERMAL IR SIGNATURES

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ABSTRACT

The purpose of this study was to determine whether hyperspectral (thermal/IR) data could be used to characterize infrastructure in the urban battlespace. The Future Force needs to dominate the urban battlespace to the same degree that the current force dominates open terrain. This can be accomplished by enabling greater Urban Battlespace Environment (U-BE) awareness through the decision phases of USECT (Understand, Shape, Engage, Consolidate, Transition). The Future Force needs tools that use automated prediction, pattern recognition, and reasoning decision support to understand the battlespace environment in a collaborative network-centric environment. Infrastructure classification using hyperspectral IR data from remote sensors will help fill this need.

To approach this problem, we sought to determine whether Thermal/IR spectral data could be used to distinguish between pavements and rooftops in the urban environment. The surface temperatures of pavements and rooftops were modeled as a function of time and environmental conditions using 1-D heat transfer theory. The model was implemented in MATLAB® using a finite difference approach that accounted for various soil depths, pavement materials and thicknesses, roof insulations, and roof types. Simulations were run with weather data from the typical meteorological year (TMY) data sets derived from the 1961-1990 National Solar Radiation Data Base (NSRDB). Theoretical thermal signatures for rooftops and pavements were developed for various days of the TMY. Thermal/IR data acquired with the 15-channel (0.45µm - 12.2µm) Advanced Thermal and Land Applications Sensor (ATLAS) for the Atlanta area were used to verify the model. The simulated thermal signatures were compared with actual ATLAS data for May 1997 and showed very good agreement. Several analyses were carried out to determine both visually and statistically if the spectral information could distinguish between rooftops and pavements. Test locations were ground-proofed in order to validate results of different analysis techniques. Additionally, a Normalized Thermal Index (NTI) analysis was performed using the ATLAS Thermal/IR bands. Bands 13 (9.6 – 10.2 µm) and 14 (10.2 – 11.2 µm) provided the best clarity for pavements and bands 10 (8.2 – 8.6 µm) and 15 (11.2 – 12.2 µm) were best for rooftops.

1. INTRODUCTION

1.1 Background

Remote sensing is the collection of data and information about an object from a distance. Remote sensing has been used for everything from city planning to intelligence gathering. The collection methods range from land based data acquisition to sensors placed on helicopters, planes, unmanned arial vehicles (UAV's) and satellites. There are many sensor technologies used for remote sensing, but the majority utilize the electromagnetic spectrum.

The emergence of alternative sensors allows greater feature delineation due to increased spatial and spectral resolution. Older sensor platforms, such as the Landsat Thematic Mapper, had spatial resolutions greater than 30 m, which do not provide enough detailed information for urban applications. Newer platforms, such as the Advanced Thermal and Land Applications Sensor (ATLAS), have spatial resolutions less than 10 m. The increased spatial resolution is crucial for distinguishing between buildings and other characteristics of the urban landscape

The increase in sensor spectral resolution has encouraged their use for material identification. Many materials have a distinctive spectrum in the hyperspectral region. However even using the most advanced hyperspectral remote sensing techniques it is still not possible to distinguish clearly between pavements and roofs (Herold, 2004). Their hyperspectral spectra are similar because they are made of similar materials. However, because the material application is different, we hypothesized that the thermal emissions of pavements and rooftops will vary

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throughout the day due to their differing construction techniques and thermal masses. For example, the thermal emissions of an asphalt parking lot should vary slowly throughout the day because the earth is a large thermal mass that moderates the solar heating of the pavement. Conversely, an asphalt roof should have great temperature swings because it is insulated from a thermal sink.

Mapping the urban environment and separating the urban landscape into the broad categories of open space, green space, pavements and buildings (roofs) is important to Field Commanders. In urbanized battlefields soldiers are required to negotiate partially known terrain, enter unknown buildings and encounter other man-made structures in anti-insurgency and other operations. This situation presents a severe disadvantage and threat to our war fighters, with the enemy well equipped with familiarity and knowledge about their built environment and building use. The results of this research will provide information necessary to ensure superior situational awareness through improved knowledge about the classification of infrastructure in the Urban Battlespace.

1.2 Objective

The research objective was to see if Thermal/IR remote sensing techniques could be used to discriminate between pavements and roofs.

1.3 Approach

There were three distinct phases to this study: (1) developing a solar heating model for pavements and roofs, (2) verifying this model with actual data, and (3) differentiating between pavements and roofs using the normalized thermal index (DTI) technique. The underlying assumption of our work is that the thermal emissions of pavements and rooftops will vary throughout the day due to their differing construction and thermal masses. We modeled both the pavement and rooftop as a one-dimensional object with varying layers based on the composition of the different surfaces. With this model we demonstrated the difference between the thermal signatures of rooftops and pavements through the course of a typical day. The model was then extended to various types of pavements and rooftops to validate the use in a varying urban landscape.

In order to verify our model we needed high spatial resolution Thermal/IR image data for an urban environment, preferably day and night data in order to observe both the heating and cooling effects. Coincidentally, researchers from the National Aeronautics and Space Administration (NASA) had conducted a study on the use of remote sensing data to assess urban thermal landscape characteristics as a means for developing more robust models of the urban heat-island effect (Quattrochi, 2000). For this NASA study data was collected using the ATLAS platform for four U.S. cities: Atlanta, Georgia; Baton Rouge, Louisiana; Salt Lake City, Nevada; and Sacramento, California. Our model was validated with the ATLAS data for Atlanta.

The ATLAS Atlanta data was also processed using a Normalized Thermal Indexing technique. Several analyses were carried out to determine both visually and statistically if the fine spectral information could distinguish between roofs and pavements. Image processing (IP) techniques were applied to the imagery, focusing in on the thermal bands, bands 10 to 15. The criteria for a desirable NTI are: (a) for the same band ratio, the means should be as widely separated as possible, (b) for each cover type the peak should be well defined (i.e. the standard deviation should be small), and (c) for each cover type, there should be only one well-defined peak.

2. SOLAR HEATING MODEL

2.1 Theory

To predict the surface temperatures of pavements and roofs, we used a one-dimensional heat transfer model. The development of this model was based on the model by Bentz, 2000. It accounts for heat flow through three mechanisms: conduction, convection, and radiation (Figure 1).

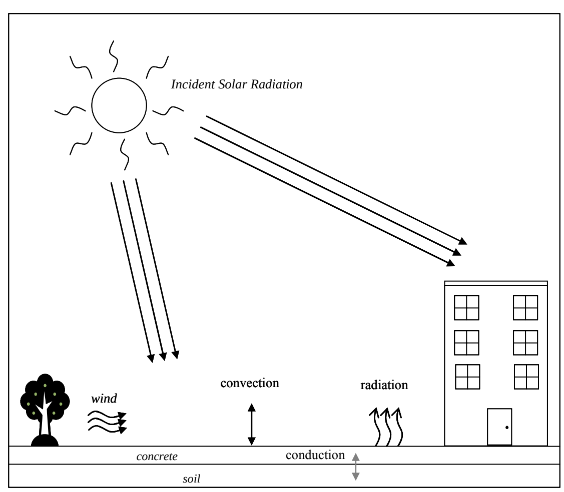

Figure 1. Diagram of the solar heating model.

The first of these, conduction (in W/m^2), is given by Equation 1:

$$Q_{\text{conv}} = k_{\text{conc}} \times \frac{(T_0 - T_1)}{\Delta x} \qquad (1)$$

where k_{conc} (in W/mºC) is the thermal conductivity of the concrete, T_o and T_1 are the surface temperature and internal temperature, respectively, and Δx is the spacing between nodes.

Convection (in W/m^2) is given by Equation 2:

$$Q_{\text{conv}} = h_{\text{conv}} \times (T_0 - T_{\text{ambient}}) \qquad (2)$$

where $T_{ambient}$ is the ambient air temperature, and h_{conv} (in W/mºC) is the convection coefficient. The convection coefficient is generally based on the wind speeds. We used the equations cited by Bentz:

$$\begin{aligned} h_{\text{conv}} &= 5.6 + 4.0 \times v_{\text{wind}} \ \text{ for } v_{\text{wind}} \le 5\,\text{m/s} \\ h_{\text{conv}} &= 7.2 \times v_{\text{wind}}^{0.78} \quad \text{ for } v_{\text{wind}} > 5\,\text{m/s} \end{aligned} \qquad (3)$$

where v_{wind} is the wind speed in m/s.

The radiation component of our model consists of two parts. The first being the heat transfer on the top surface due to radiation absorbed from incoming sunlight. This radiation is given by Equation 4:

$$Q_{\text{sun}} = \gamma_{\text{abs}} \times I \qquad (4)$$

where I is the incident solar radiation (in W/m^2) and γ_{abs} is the solar absorptivity of the concrete.

The second part of the radiation is the emissions of the concrete to the sky. This heat flow is given by Equation 5:

$$Q_{\text{sky}} = \sigma \times \varepsilon \times (T_{0\text{K}}^4 - T_{\text{sky}}^4) \qquad (5)$$

where σ is the Stefan-Boltzmann constant (5.669 x 10^{-8} W/(m^2 ºC^4)), ε is the emissivity of the concrete, T_{0K} is the concrete surface temperature, and T_{sky} is the calculated sky temperature. The sky temperature is calculated with Equation 6:

$$T_{\text{sky}} = \varepsilon_{\text{s}}^{1/4} \times T_{\text{ambient}} \quad (T \text{ in } ^\circ\text{K}) \qquad (6)$$

where ε_s is the sky emissivity given by Equation 7:

$$\varepsilon_{\text{s}} = 0.787 + 0.764 \times \ln\left(\frac{T_{\text{dew}}}{273}\right) \times F_{\text{cloud}} \qquad (7)$$

where T_{dew} is the dewpoint temperature and F_{cloud} is the cloud cover factor given by Equation 8:

$$F_{\text{cloud}} = 1.0 + 0.024 \times N - 0.0035 \times N^2 + 0.00028 \times N^3 \qquad (8)$$

where N is the “tenths of cloud cover.”

The equations above were used in conjunction with a finite difference solution of the heat equation given by Adam Powell’s lecture “Finite Difference Solution of the Heat Equation” (Powell, 2002). The solution results in the temperature at each time step $T_{i,n+1}$ as shown by Equation 9:

$$T_{i,n+1} = T_{i,n} + \Delta t \left[\frac{\alpha \left(T_{i-1,n} - 2 \times T_{i,n} + T_{i+1,n} \right)}{\Delta x^2} + \frac{q}{\rho \times c_{\text{p}}} \right] \qquad (9)$$

where Δt is the time step, Δx is the node spacing and q is the heat generated and c_p is the heat capacity. The stability of the model limits the time step Δt to be given by Equation 10:

$$\Delta t \le \frac{\Delta x^2}{2\alpha} \qquad (10)$$

2.2 Implementing the Model

Bentz uses a 1-D finite difference grid with a varying number of nodes. The nodes are equally spaced throughout the concrete slab. For parking lots, the model assumes that under the concrete there is a layer of soil. The soil acts as a sink at 1m below the concrete, and is assumed to be at a constant temperature of 13 ºC. Slight variations of this soil temperature do not affect the results (Bentz, 2000).

The model above has been used successfully in studies with purposes similar to ours, thus providing a good basis for our calculations. We developed a MATLAB® program to implement the model using the finite difference technique and adapted it for pavements and rooftops by allowing for multiple layers. Data from meteorological files were used to extrapolate ambient conditions and parameters. The general flow of the program consists of three steps. First the user inputs and modifies the desired conditions and surfaces to model. Next, the program creates four arrays containing the temperature at the surface as well as intermediate levels in the desired materials. Last, the program plots the pertinent information in seven different plots.

The program requires the user to input the thermal conductivity, thermal diffusivity, and depth of each layer. In addition, the top layer emissivity and solar absorptivity are also required. Next, the user inputs the desired date, and which of the two types of structures is to be modeled. The program returns the plots as well as a spreadsheet file containing the surface temperatures throughout the course of the day.

Meteorological data is given in hourly averages of the ambient conditions. From this data, the program linearly interpolates data for every second of the day. Data is graphed along with the calculated temperatures in one of the plots generated by the program. It is the ambient conditions that govern the contours of each temperature profile. However, it is the material composition and thermal properties of each layer as well as the structure that give the temperature profile its own unique shape.

2.3 Theoretical Thermal Signatures

The thermal signatures obtained from these models were analyzed to determine if there was a measurable difference between the thermal signatures of rooftops and pavements. As shown in Figure 2, the pavement and rooftop temperatures differ by approximately 20 ^{o}F around noon.

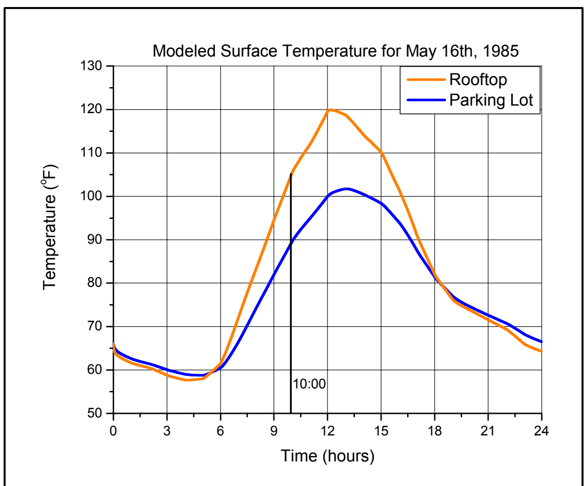

Figure 2. Roof and pavement simulation for a typical sunny day in May.

The model was modified to test for varying ballast, membranes, insulations, soil depths, and other factors (such as sudden clouds). The results showed the same trends seen in Figure 2. This result led us to the conclusion that with the proper sensors acquiring data at the correct time of day an appreciable difference should be able to be seen between pavements and rooftops.

The next step was to compare the simulated results with ATLAS data collected for downtown Atlanta. This data was collected in May 1997. We assumed that the ATLAS data was collected on a relatively clear sunny day. ATLAS data was analyzed by Dr. Quattrochi and calibrated for atmospheric conditions (Quattrochi, 2000). In this paper, he presented a colorized image of downtown Atlanta, where the colors are assigned to temperature ranges. Shadows around large structures show up as cool areas and form a basis for estimating the time of day that this data was collected. We estimated that the data was collected mid morning or around 10:00 AM. From his image, we were able to ascertain individual roofs and pavements by comparing to satellite images. The rooftops show up as red and the pavements as green. He assigned the following temperatures to these colors; red was 104.9 ^{o}F, and green was 88.9 ^{o}F. If we look again at Figure 2, we see a line drawn at 10:00 AM. This shows that our simulation predicted the temperature of the pavements to be 90 ^{o}F, and the rooftops to be 105 ^{o}F at 10:00. This shows very good agreement with the ATLAS data and gives us confidence that the model simulations are reasonable.

3. REMOTE SENSING

3.1 Background

In our study we used data at a 10m spatial resolution taken over Atlanta, GA. The data was obtained in May of 1997 using the ATLAS sensor system on board a NASA Stennis LearJet. The bands of interest were the six thermal infrared bands shown in Table 1. The thermal bands range from 8.20 μm to 12.2 μm, and provide valuable information about urban landscape characteristics. A GPS location of the acquired data was used to ground proof the information. The spatial resolution of 10m is instrumental in discerning rooftops from parking lots.

Before the data for Atlanta could be used, it needed to be corrected for the attenuation effect of the atmosphere. The data was originally recoded as an 8-bit format with integer values ranging from 0 to 255. This data was adjusted for transmittance and path radiance variations, along with various calibrations for temperature measurements. This was completed using the MODTRAN program developed by the United States Air Force Geophysics Laboratory. The data was manipulated in order to form a false color composite image to show specific information about the urban landscape. This manipulation was done by a normalized difference algorithm.

The Advanced Thermal and Land Applications Sensor (ATLAS) data was used for the purpose of distinguishing between pavements and roofs. Data was collected at approximately 5032 meters above mean terrain resulting in a spatial resolution of approximately 10m. ATLAS data for an area centered on Atlanta, GA was acquired. A small section of the available data was cut out (Figure 3) to provide a manageable amount of data to process and store. Various analyses were carried out to determine if the thermal data provides insight into the location of roofs and pavements. Image processing techniques were applied to the imagery. The best results were obtained using a Normalized Thermal Index (NTI) for pavements and rooftops.

Table 1. ATLAS channel specifications.

	Channel	Band limits (µm)
Visible Bands	1	0.45 – 0.52
	2	0.52 – 0.60
	3	0.60 – 0.63
	4	0.63 – 0.69
Near Infrared (NIR) Bands	5	0.69 – 0.76
	6	0.76 – 0.90
	7	1.55 – 1.75
	8	2.08 – 2.35
Thermal Infrared (TIR) Bands	9	3.35 – 4.20
	10	8.20 – 8.60
	11	8.60 – 9.00
	12	9.00 – 9.40
	13	9.60 – 10.2
	14	10.2 – 11.2
	15	11.2 – 12.2

On this focused section that includes downtown Atlanta, several analyses were carried out to determine both visually and statistically if the spectral information could distinguish between roofs and pavements. Image processing (IP) techniques were applied to the imagery, focusing in on the thermal bands (bands 10 to 15). Eight ground-truth points were identified as either rooftops or pavements. These points are also shown in Figure 3. The points were used to determine the accuracy of the different analysis techniques.

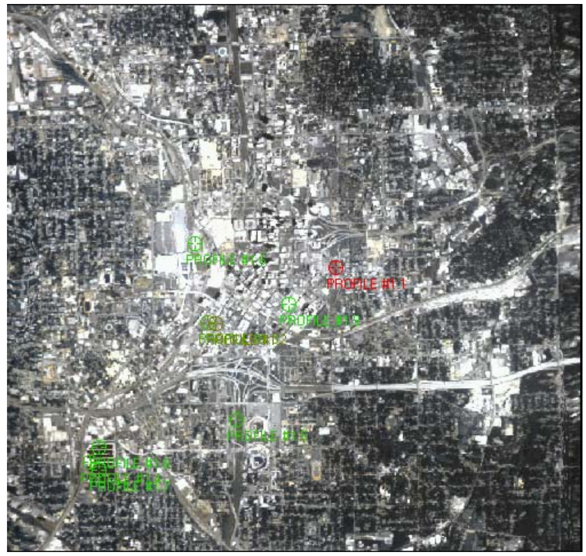

Figure 3. Visible image of Downtown Atlanta with initial test locations.

3.2 Standard Image classification

The focused section of downtown Atlanta was analyzed with a standard image classification scheme (Unsupervised Isodata). The algorithm is an iterative procedure that creates cluster vectors from the data. First this procedure was carried out using all 15 bands of data provided by the ATLAS. While some of the ground-truth points were accurately distinguished, there was a 33% confusion rate within the points. Next, the thermal bands were considered on their own, with a small section of results shown in Figure 4.

Figure 4. Standard Image classification scheme (Unsupervised Isodata) with only the six thermal bands (bands 10-15).

When only the thermal bands were taken into account a 56% confusion rate was seen. Moreover the clusters with more than one point had 0% separation rate.

3.3 Normalized Thermal Index Analysis

A common remote sensing technique used in analysis is to divide one satellite band by another in the same location. A small ratio implies small change, and a large ratio means there is a greater spectral response. This technique is used for many applications such as minerals in earth ores. However, for more sensitive comparisons a more sophisticated technique is shown in Equation 11.

$$\frac{\mathrm{Band}(x)-\mathrm{Band}(y)}{\mathrm{Band}(x)+\mathrm{Band}(y)} \tag{11}$$

This process is called a "normalized index" and results in values ranging from -1 to +1. The normalization allows for comparison between many different bands. The procedure is used for detailed vegetation research. A Normalized Thermal Index (NTI) was calculated for each of the 15 unique combinations of the thermal bands. In analyzing the results the desire was to have the rooftops and pavements shown as distinctly separate. In Figure 5 the NTI image for band 13 vs band 15 shows some distinction between rooftops (in white) and the highways (in black). Other rooftops and pavements are not so well defined in the image with NTI values very close to each other. Applying thresholds to the NTI image may subjectively provide better results as shown in Figure 6.

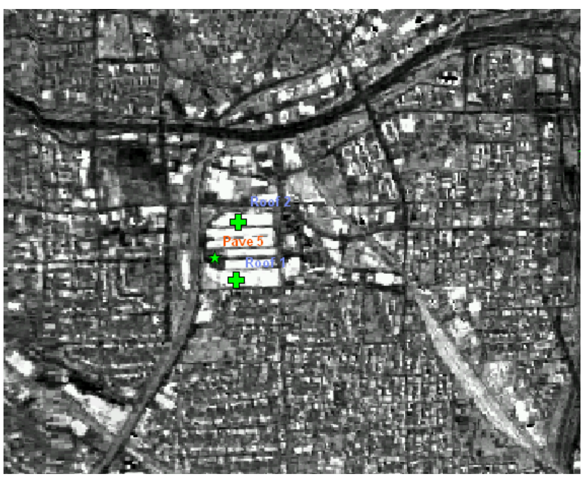

Figure 5. The NTI image for band 13 vs band 15.

Statistical analysis of the NTI technique was conducted to find the range, mean, and standard deviation of cells that were of the pavement or rooftop type. The best results came from the combination of band 13 and band 14 in which the two means were separated by 0.023 (higher than the average of 0.019). In the images the roads would be well categorized and appear black. However, the rooftops would sometimes be white, and others would be gray. This undesired result leads us to one more improvement on the technique.

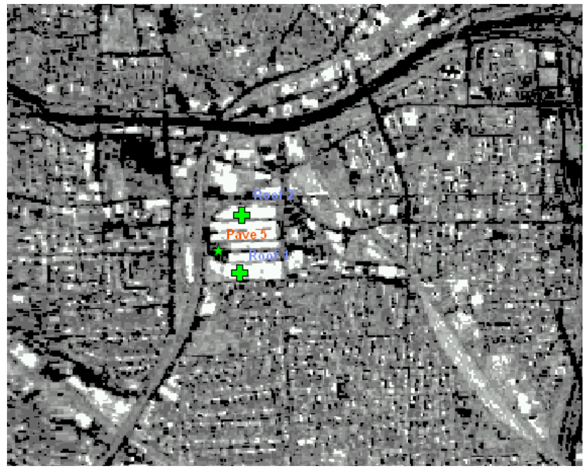

Figure 6. Threshold Image NTI > 0.0568 is roof and NTI < 0.0234 is pavements.

Through the statistical approach the combination chosen correctly identified pavements. Through inspection of the statistics another combination was found to give positive rooftop identification. By searching for an NTI with narrow peaks for both rooftops and pavements with a large mean spread the combination of band 10 and band 15 was chosen. When the band is colored as show in Figure 7 with the NTI ranges shown the ground-truth rooftops are accurately identified.

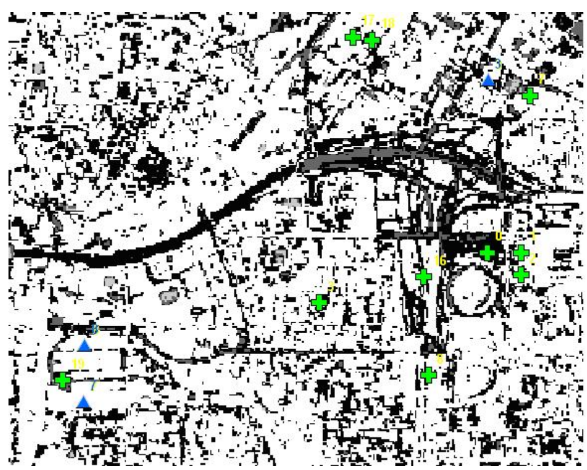

Figure 7. An NTI from band 13 vs band 14 shows pavements well.

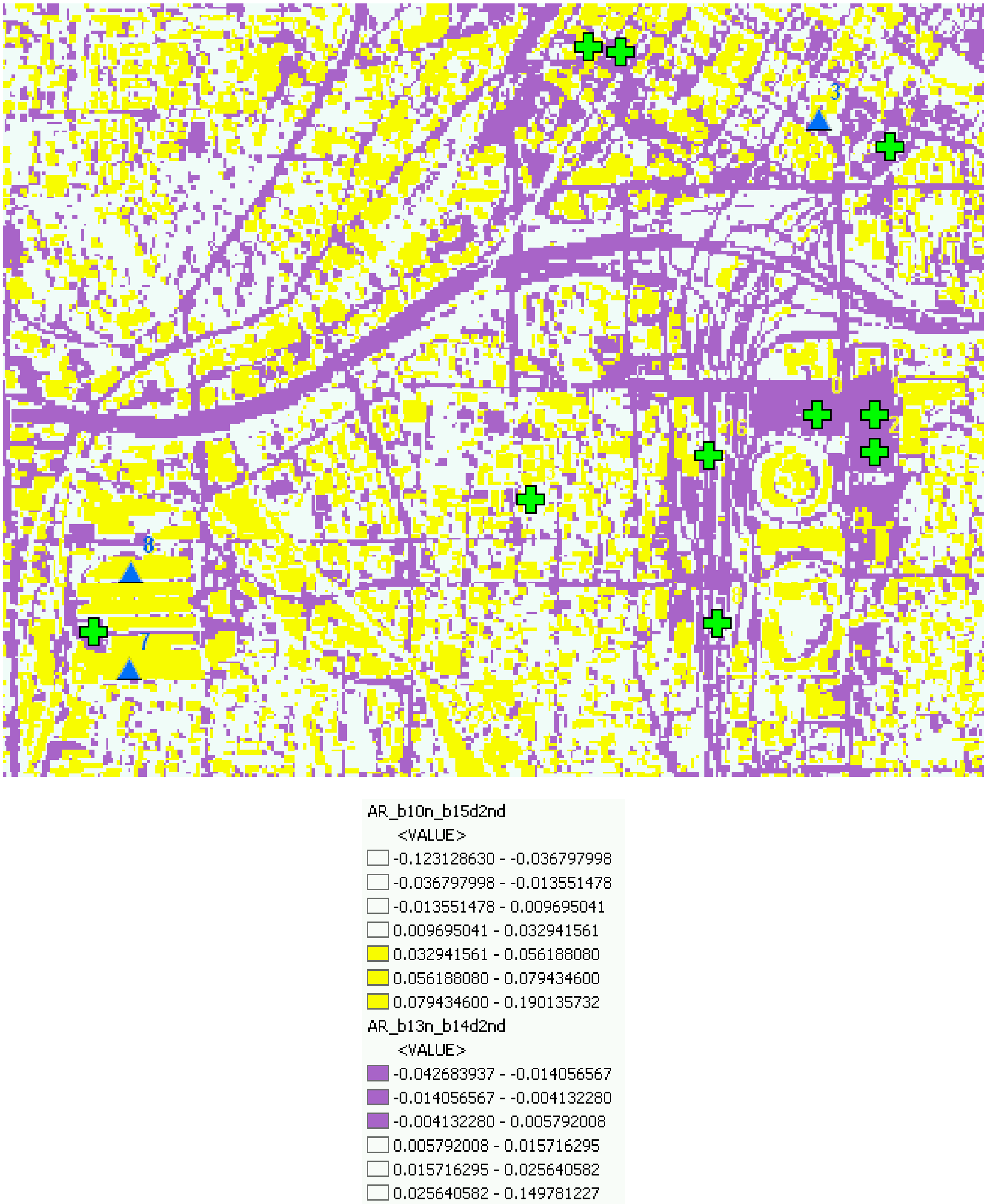

Figure 8. An NTI from band 13 vs band 14 for pavements and band 10 vs band 15 for rooftops.

Therefore, an image combining the two combinations provides the most information. The combination of band 13 and band 14 is colored to show the pavements, and the combination of band 10 and band 15 is colored to show the rooftops, and the two resulting images are layer and show in Figure 8. This image shows pavements in purple and rooftops in yellow, and accurately identifies the ground-truth points.

CONCLUSIONS

The original hypothesis that different sink temperatures and varying thickness of materials provides rooftops and pavement unique thermal signatures was verified. A 1-D heat transfer model was developed to predict the surface temperatures of pavements and roofs based on varying environmental conditions. This model was implemented in MATLAB® using a finite difference method and simulations were run for various roof and pavement configurations and materials. The simulated temperatures were compared to ATLAS data (Quattrochi, 2000) for downtown Atlanta and showed very good agreement.

We tested the various band combinations of the Atlas thermal spectral bands to determine how well we might be able to use these bands to distinguish roofs from pavements simply on their thermal characteristics. In other words, this was done to develop a reliable Normalized Thermal Index (NTI).

Although both statistically and visually there are combinations that provide a better result, the analysis suggests that the resultant data does not exhibit a clear choice in terms of the criteria set up to select a reliable NTI with the Atlas Sensor. The best statistically determined choice was checked in detail against the stated criteria and was found to not result reliably in fulfilling the developed criteria. The best choice by inspection resulted in a better definition of rooftops, but poorer for pavements. It is therefore proposed that two NTIs be used, one to define pavements and one to define rooftops. The NTI procedure produces well defined images that accurately identify ground-truth points.

The purpose of this study was to determine whether Thermal/IR spectral data could be used to distinguish between pavements and rooftops in the Urban Battlespace Environment. It is suggested that different cooling rates due to the thickness and substrate may well be detectable if imagery taken at different times of the day were compared, particularly if mid afternoon imagery were compared to after midnight imagery. In this case, subtracting the daytime NTI from the nighttime NTI is likely to result in a clear distinction between the two materials. We plan to continue our study using data, both day and night, from the other cities in the NASA study.

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REFERENCES

Bentz, D. P. (2000). A Computer Model to Predict the Surface Temperature and Time-of-Wetness of Concrete Pavements and Bridge Decks. Building and Fire Research Laboratory, Gathersburg, MD-USA.

Herold, Martin (2004). Spectrometry for urban area remote sensing – Development and analysis of a spectral library from 350 to 2400 nm, Remote Sensing of Environment, 91 (2004) 304-319.

Powell, A. (2002). Finite Difference Solution of the Heat Equation. Lecture 22.091 MIT, Cambridge, MA-USA.

Quattrochi, D. (2000). A Decision Support Information System for Urban Landscape Management Using Thermal Infrared Data, Photogrammetric Engineering & Remote Sensing, Vol. 66, No. 10, October 2000, pp. 1195 – 1207.